

CAPACITIVE DISTANCE SENSOR

CROSS-REFERENCE TO RELATED APPLICATION

This application is a division of U.S. Patent Application number 5 09/019,496 filed February 5, 1998 and allowed on July 31, 2001, entitled "Capacitive Distance Sensor, which was a continuation-in-part of U.S. Patent Application number 08/799,548, entitled "Capacitive Distance Sensor," filed February 13, 1997, now abandoned. Additionally, this application is related to U.S. Patent Application number 09/179,923, filed October 27, 1998, and allowed September 24, 2001.

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TECHNICAL FIELD

The present invention relates to a capacitive distance sensor, in particular, a small-distance (micrometric to millimetric) sensor.

15 BACKGROUND OF THE INVENTION

Small-distance sensors are used, among other things, as pressure, proximity, roughness, mechanical stress and acceleration sensors, for example, in integrated microphony and for acquiring fingerprints.

For fingerprint acquisition in particular (to which reference is made 20 herein purely by way of example of a preferred application of the present invention), known sensors include various types, such as optical, piezoelectric, variable-conductance, thermal, ultrasonic and capacitive, the most promising of which in terms of precision, size, production and cost are capacitive sensors.

Capacitive sensors are based on the principle that the capacitance 25 between two plates is inversely proportional to the distance between them, so that, using the contacting dermal tissue itself as the second plate of the sensor capacitor, and by determining the capacitance, it is possible to locate the ridges and grooves of the fingerprint. This is the principle used in U.S. Patent No. 5,325,442 to Knapp, which relates to a sensor comprising an array of elementary cells, each comprising a sensitive 30 electrode and an electronic switching device. The electrode is coated with dielectric material, such as passivation oxide or a polymer compound, onto which the epidermis

is placed. When a cell is selected, a predetermined variation in potential is applied to the electrode to induce at the terminals an appropriate variation in charge. The extent of variation in charge depends on the capacitance associated with the electrode and is read by amplifying elements connected to the output of the device. To improve 5 efficiency, the above patent suggests a surface grid connected to a reference potential to appropriately bias the skin tissue.

In the above known capacitive sensor, the capacitance between the plates of a capacitor varies in inverse proportion to the distance between the plates, which therefore poses the problem of normalizing the resulting data. In particular, if the 10 capacitance being measured is very small, as in the application in question, serious difficulty is encountered in detecting the charge and discriminating between the various intermediate charge levels corresponding to different gray levels of the image to be generated in the presence of a low signal/noise ratio.

15 SUMMARY OF THE INVENTION

It is an object of the present invention to provide a sensor designed to overcome the drawbacks typically associated with known technology.

A preferred embodiment of the present invention is directed to a capacitive distance sensor for measuring small distances. The distance sensor includes 20 a first plate positioned facing a second plate such that the first and second plates define a distance to be measured therebetween and form a capacitive element therebetween. The distance sensor also includes an amplifier having an input and an output. The capacitive element is connected between the input and the output to form a negative feedback branch.

25 In practice, according to the present invention, the detecting capacitor, the distance between the plates of which is to be determined, is placed in a negative feedback loop, thus inverting between the denominator and the numerator the dependence of the output voltage on the distance between the plates.

A preferred embodiment of the present invention is directed to a sensor 30 device, integrated on a single semiconductor chip, that senses a distance between the sensor device and an object such as a human finger. The sensor device includes first

and second coplanar plates positioned adjacent to the object to form first and second capacitances between the object and the first and second plates, respectively. The sensor device includes an amplifier having an input connected to the first plate and an output connected to the second plate to form a negative feedback branch that includes
5 the first and second capacitances.

Fingerprint and other biometric sensors formed in accordance with the present invention will have application in preventing the unauthorized use of cellular phones, laptop computers, automobiles, automated teller machines, credit/debit card readers, POS terminals, and smart cards. They are also useful in authenticating
10 electronic financial transactions, personal e-mail, providing access to buildings, etc. Biometric identification, such as personal identification and authentication alternatives which could be accomplished by mounting a sensor as taught by the present invention include hand or finger shape, facial shape, and facial features. In addition, the sensor device of the present invention could be used for non-biometric sensing, such as
15 handwriting detection, switch actuation, and any other device requiring sensitivity to object proximity.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a sensor device for acquiring personal feature scans,
20 such as fingerprints.

Figure 2 shows a detail of a cell of the sensor device shown in Figure 1.

Figure 3 shows an electric equivalent of the cell shown in Figure 2.

Figure 4 is an illustration showing a finger positioned on two adjacent cells of the sensor device shown in Figure 1.

25 Figure 5 is a block diagram of the sensor device shown in Figure 1.

Figure 6 is a circuit diagram of one embodiment of the cell shown in Figure 2.

Figure 7 is an image of a fingerprint obtained from the sensor device shown in Figure 1.

DETAILED DESCRIPTION OF THE INVENTION

Figure 1 shows a sensor device 1, preferably embodied in an integrated chip, comprising a number of cells 2 arranged to form an array 3 and each constituting an elementary sensor. The simplicity of the individual cells 2 enables the sensor device 5 1 to be implemented in integrated from on a single semiconductor chip.

The sensor device 1 also comprises a horizontal scanning stage 5 and a vertical scanning stage 6 for enabling one of the cells 2 at a time according to a predetermined scanning pattern. Preferably, to read the cells, stages 5, 6 enable the outputs of the cells 2 sequentially, and comprise shift registers. Alternatively, other cell 10 reading devices could be employed, such as a random access decoder that reads addressed cells rather than sequentially scanning the cells 2.

The sensor device 1 also comprises a supply and logic stage 7, which supplies the components of the device with power (including the cells 2), feeds the necessary reference voltages, and controls the sequence of steps provided for (as 15 explained in detail below). In particular, Figure 1 shows that the supply and logic stage 7 includes a voltage source 12 for generating a reference voltage variation ΔV_R . A buffer 8 is connected to the outputs of all the cells 2, and supplies sequentially, at output 10 of the sensor array 3, the signals present at the outputs of the cells 2 enabled by scanning stages 5, 6.

As shown in Figure 2, each cell 2 comprises a low-power inverting amplifier 13 of gain A , in turn presenting an input 16 at input voltage V_i , and an output 17, at output voltage V_o , which also defines the output of cell 2. Each cell 2 also includes first and second plates 23, 24 of equal area positioned facing the skin surface 18 of the finger being printed. Preferably, the first and second plates 23, 24 are 25 coplanar with respect to each other. A reset switch 19 is connected between the input 16 and output 17 of the inverting amplifier 13. An input capacitor 20 is connected between an input 21 of the cell 2 and the input 16 of the inverting amplifier 13.

More specifically, the first and second plates 23 and 24 are respectively connected to the output 17 and the input 16 of the inverting amplifier 13, thus realizing 30 a charge integrator. The first and second plates 23 and 24 are covered with a dielectric insulating layer 25 that covers the face of integrated sensor device 1, including the

entire array 3 of cells 2. In use, therefore, skin surface 18 forms a third plate facing the first and second plates 23, 24, and defining with them a pair of series capacitors feedback connected between input 16 and output 17 of inverting amplifier 13. Accordingly, a contact grid is not required to bias the skin surface at constant voltage.

5 The switch 19 is a controlled switch formed using any known technology (e.g., a MOS switch) and receives a control signal R from the supply and logic stage 7. The input 21 of the cell 2 is also connected to the supply and logic stage 7 to receive a voltage signal ΔV_R as explained below.

To acquire fingerprints, the skin surface 18 is placed on the surface of
 10 integrated sensor device 1, at array 3, to complete the pairs of capacitors forming the feedback loops of amplifiers 13 of all the cells 2. At the start of the measurement, the switches 19 of all the cells are closed, and the voltage level at each of inputs 21 is constant, so that the input voltage V_i of all the cells 2 is brought to the same potential as the output voltage V_o , between the supply and ground at a high-gain point or logical
 15 threshold V_t of inverting amplifier 13.

Subsequently, the supply and logic stage 7 opens all the switches 19 in parallel, and supplies all the inputs 21 with a voltage step ΔV_R , so that a charge variation $\Delta Q = C_i * \Delta V_R$ (where C_i is the capacitance of input capacitor 20) is induced at the terminals of each input capacitor 20 to permit a reading, as explained below, of the
 20 local distance "d" between the first and second plates 23, 24 and skin surface 18 facing them. Obviously, the local distance "d" varies according to whether the point being measured corresponds to a groove, a ridge or a point between the two.

Scanning stages 5, 6 then sequentially enable the reading of cells 2, so
 25 that the voltage signal at the output 10 of the buffer 8 is supplied to a system for representing the distance, in known manner, by means of gray levels, and so providing a three-dimensional display of the skin surface.

The way in which the local distance "d" between the first and second plates 23, 24 of each cell 2 and the third plate formed by the skin surface 18 is detected will now be described with reference to the equivalent electric diagram in Figure 3.

Figure 3 shows an equivalent input capacitance 30 and an equivalent output capacitance 31 of the inverting amplifier 13 and the charge flow direction (indicated by the arrows) corresponding to the voltage variations at the plates. Figure 3 also shows a first feedback capacitor 33 formed by the first plate 23 and the skin surface 18 and a second feedback capacitor 34 formed by the second plate 24 and the skin surface 18.

Assuming C_l is the equivalent input capacitance 30 of inverting amplifier 13; C_r is the total capacitance of the series-connected feedback capacitors 33 and 34; A is the gain of the inverting amplifier 13; ΔQ is the charge variation induced in the equivalent input capacitance 30 by voltage step ΔV_R ; ΔQ_i is the charge variation stored in the equivalent input capacitance 30 as a result of step ΔV_R ; ΔQ_r is the charge variation in the feedback branch formed by the series connection of the feedback capacitors 33, 34; ΔV_i is the voltage step at the input 16 of the inverting amplifier 13; ΔV_o is the corresponding voltage variation at the output 17 (equal to $-A \Delta V_i$); S is the size of the top surface (surface facing the skin surface 18) of each plate 23, 24 of capacitors 33, 34; ϵ_0 is the electric constant (seeing as, in the fingerprinting application, the average distance between the skin surface 18 and the insulating layer 25 - typically 60 μm at the grooves - is greater than the thickness of layer 25 - typically 2 μm); and \underline{d} is the local distance between plates 23, 24 and skin surface 18 (approximately the same for both plates 23, 24, in view of the very small size of cells 2 - typically about 45 μm); then total feedback capacitance C_r is given by the following equation:

$$C_r = \frac{S\epsilon_0}{2d} \quad (1)$$

Moreover:

$$\Delta Q = \Delta Q_i + \Delta Q_r = C_l \Delta V_i + C_r (\Delta V_i - \Delta V_o) = -\frac{\Delta V_o}{A} (C_l + C_r) - \Delta V_o C_r$$

$$\Delta V_o = -\frac{\Delta Q}{\frac{C_1}{A} + \left(1 + \frac{1}{A}\right)C_r} \quad (2)$$

Substituting (1) in (2) gives:

$$\Delta V_o = \frac{\Delta Q}{\frac{C_1}{A} + \left(1 + \frac{1}{A}\right) \frac{S\varepsilon_o}{2d}} = -\frac{2\Delta Qd}{\frac{2C_1d}{A} + \left(1 + \frac{1}{A}\right)S\varepsilon_o} \quad (3)$$

Assuming $A \gg 1$, (3) becomes:

$$5 \quad \Delta V_o = d \frac{2\Delta Q}{S\varepsilon_o} \quad (4)$$

Consequently, by virtue of the negative feedback effected by capacitive coupling the output 17 and input 16 of the inverting amplifier 13 via the skin tissue, the variation in output voltage as a result of the charge step is directly proportional to the distance between the plates 23, 24 and the skin surface 18, in turn dependent on the
10 three-dimensional structure of the skin. For a fixed amount of the input voltage step ΔV_i , the output voltage of the inverter 30 will range between two extremes, depending on feedback capacitance value: (i) the upper saturation level if no feedback capacitance is present; (ii) a value close to the logical threshold when the feedback capacitance is large.

15 With appropriate amplification levels (e.g., 1000-2000), it is possible to detect differences in capacitance of about ten fF and hence micrometric distances. The output signals of the device according to the invention are therefore such, when converted into gray levels, as to provide a highly reliable representation of the three-dimensional structure of the skin surface.

20 The operation of the sensor device 1 can be further appreciated with regard to Figure 4, which is an illustration of the skin surface 18 positioned on first and second adjacent cells 2A, 2B of the sensor device 1. It is to be understood that the present invention will have application to thumbs, palms, and any contact surface where an image is desired. Each of the adjacent cells 2A, 2B is substantially identical to the
25 cell 2 shown in Figures 2-3, and thus, additional detailed discussions of the elements of

cells 2A, 2B are being omitted for simplicity. The elements of the adjacent cells 2A, 2B are marked with labels corresponding to the labels of Figures 2 and 3 with an "A" and a "B" added to the cells 2A and 2B, respectively.

The skin surface 18 shown in Figure 4 includes a ridge 36 adjacent to the
5 first cell 2A and a valley 38 adjacent to the second cell 2B. As a result, the first and
second cells 2A, 2B will each produce different capacitive coupling responses in the
sensor device 1. Accordingly, the first cell 2A will sense a smaller distance d1,
signifying the ridge 36, than the second cell 2B, which senses a larger distance d2,
signifying the valley 38. The distance d2 sensed by the second cell 2B will be the
10 average of a distance d2a between the first plate 23B and the portion of the skin surface
18 directly above the first plate 23B and a distance d2b between the second plate 24B
and the portion of the skin surface 18 directly above the second plate 24B. From a
lumped-model point of view, this structure realizes a two series-connected capacitors
scheme that can sense the difference between a contacting member, a ridge, and a non-
15 contacting member, a valley.

A block diagram of the sensor device 1 according to one embodiment of
the invention is shown in Figure 5. The sensor device 1 includes the sensor array 3
which is coupled by a digital to analog (D/A) converter 40 to an I²C interface and
control device 42 and a bias generator 44. For simplicity, the horizontal and vertical
20 scanners 5,6 and the output buffer 8 are not shown in Figure 5, but are part of the sensor
device 1 shown in Figure 5. The sensor device 1 also includes an oscillator 46 and
timing generator 48 coupled to the sensor array 3. The D/A converter 40, I²C interface
and control device 42, bias generator 44, oscillator 46, and timing generator 48 together
implement the functionality of the supply and logic unit 7 discussed above. The I²C
25 interface and control device 42 provides a bidirectional communication protocol that
enables the sensor device 1 to communicate with a controller, such as a standard
computer. The D/A converter 40 converts digital control signals from the I²C interface
and control device 42 into analog signals that are transmitted to the sensor array 3 to
control the scanning of the cells 2 by the horizontal and vertical scanners 5,6. The D/A
30 converter 42 also provides analog biases, such as the voltage step V_r. The timing
generator 48 takes a single clock signal from the oscillator 46 and generates timing

signals that are provided to the sensor array 3 under the control of the I²C interface and control device 42.

To enable the distance measurements (represented by voltages) to be output to the computer coupled to the sensor device 1, the sensor device includes an 5 analog to./digital (A/D) converter 50 coupled between the output 10 of the sensor array 3 and the computer. The A/D converter 50 also is coupled to the bias generator 44 and timing generator 48 to enable the A/D converter 50 to convert the analog voltage measurements output by the sensor array 3 to digital signals that are recognized by the computer as distance measurements. The sensor array 3 also is directly coupled to the 10 computer by a synchronization line 52 that provides the computer with synchronization signals that help the computer properly interpret the digital distance measurements received from the A/D converter 50.

A detailed schematic of the cell 2 of Figure 2 is illustrated in Figure 6. The cell 2 includes first and second transistors M1, M2 of the N-channel type and third 15 and fourth transistors M3, M4 of the P-channel type connected together in series to comprise a high gain cascode inverting amplifier 13. A first horizontal scan line (hor1) and a first vertical scan line (vert1) are coupled respectively from the horizontal and vertical scanners 5, 6 to the second transistor M2 and the third transistor M3 to ensure that only one cell at a time is powered, thereby limiting power consumption of non- 20 addressed cells. A gate terminal of the first transistor M1 is coupled by the input capacitor 20 of the cell 2 to the cell input 21. ΔV_r , as discussed above. When the voltage step ΔV_r is applied to the input node 21, a charge amount $dQ = C_i \Delta V_r$ is sunked from the amplifier input 16 as previously explained. This mode of operation is useful since by changing the amount of ΔV_r , the sensor can deal with different ranges of 25 sensed capacitances. The gate of the fourth transistor M4 is coupled to a fixed bias V_p .

The output 17 of the inverting amplifier 13 is buffered by a source follower stage (fifth transistor M5) into a vertical output line 54 by means of a sixth transistor M6. A seventh transistor M7 couples the vertical output line 54 to the output buffer 8 of the sensor device 1. The gate of the sixth transistor M6 is coupled by a 30 second horizontal scan line (hor2) to the horizontal scanner 5 and the gate of the seventh transistor M7 is coupled by a second vertical scan line (vert2) to the vertical

scanner 6, which ensures that only one cell at a time is communicating with the output buffer 8. This greatly reduces the output capacitance of the follower stage 46 since only one vertical output line at a time is connected to the output buffer 8..

The reset switch 19 is connected between the input 16 and output 17 of 5 the inverting amplifier 13 as discussed above. The reset switch 19 is designed to prevent charge injection in the input 16 from saturating the inverting amplifier 13. If the switch-off transient of the reset switch 19 is slow enough compared to the inverse of the gain bandwidth product of the inverting amplifier 13, most of the channel charge of the reset switch is injected into the output node. The reset switch 19 includes eighth 10 and ninth transistors M8, M9 with their drain terminals coupled together to the input 16 and their source terminals coupled together to the output 17. The size of the eighth transistor M8 is small in order to reduce the absolute amount of injected charge. Reducing the dimension of the eighth transistor M8 degrades the stability of the inverting amplifier 13 since it reduces the loop gain-bandwidth. In this design, the 15 ninth transistor M9 is stronger than the eighth transistor M8 and is activated at a different phase than the eighth transistor M8 is introduced. During the reset phase, both transistors M8, M9 are set, reducing resistance of the feedback loop so output ringing is contained. During charge integration, the ninth transistor M9 is first opened so its channel charge is absorbed by the eighth transistor M8. Finally, the eighth transistor 20 M8 is opened by a slow gate transient to ensure low charge-injection on the input.

In a preferred embodiment, the chip is made using a 0.7 μm CMOS digital process. The cell area is $65 \times 65 \mu\text{m}^2$, giving a 390 dpi resolution. A sample image 56 produced for a 200 x 200 window is shown in Figure 7, which clearly shows gray levels. The image disappears as the finger is removed. The power consumption 25 measured at 3 μs of a period cycle is 250 μW for the digital circuitry and 300 μW for the cell array 34 and buffer.

The sensor cells 2 described above are preferably formed using conventional silicon integrated circuit methodology. More particularly, all of the elements of the sensor device 1 shown in Figures 1-6 can be integrated on a single chip. 30 Alternatively, one or more of the elements, such as the oscillator 46, can be made separately and coupled to the integrated elements of the sensor device 1.

The sensor device shown in Figures 1-6 has at least the following advantages. In particular, as stated, the sensor device provides for a high degree of precision with no need for complex processing of the output signal. Further, the sensor device may be produced easily and integrated using current microelectronic technology
5 and is highly reliable, compact, and cheap to produce.

The sensor device according to the invention may also be used to advantage in other applications requiring precise detection of small distances.

Moreover, the simple design of each cell enables a large number of cells to be accommodated in array structures for detecting two-dimensional physical
10 quantities.

Clearly, changes may be made to the device as described and illustrated herein without, however, departing from the scope of the present invention. In particular, if fabrication techniques enabling the formation of elastic structures (micromachining techniques) are available, the electrode whose distance is being
15 measured may be connected directly to the input or output of inverting amplifier 13 to eliminate one of plates 23, 24. Moreover, all the components may be replaced by technical equivalents. For example, though an inverter such as inverting amplifier 13 is currently preferred for design and layout reasons, amplifier 13 may be implemented by any inverting or differential amplifier (e.g., an operational amplifier) in a charge
20 amplifier configuration to increase the speed of the output signal.